Imaging Space Junk with Nano-Computers on Nano-Satellites

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Concept of Operations for LLNL "Space-based Telescopes for Actionable Refinement of Ephemeris" (STARE) Program

1. Observe space object that is predicted to pass close to an operational satellite, based on conjunction analysis using AFSPC catalog

2. Transmit images and position of observation to ground

IRIDIUM 14

SV0

A constellation of 18 nano-satellites would eliminate 99% of current satellite collision warnings: 1 per decade per satellite vs. 1 per month

3. Refine orbital parameters of space object to reduce uncertainty in position estimate and improve accuracy of conjunction analysis

4. Notify operators of high-probability collision

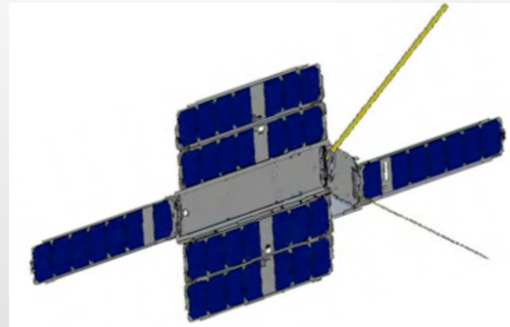
5. Operator chooses to move satellite to safe orbit

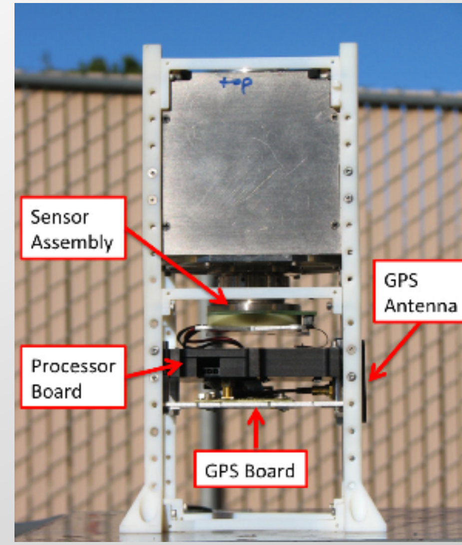
SV0 ICR Axes

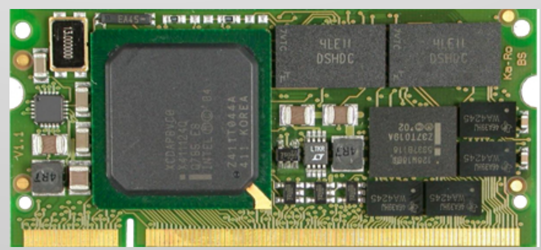
14 Feb 2012 21:10:45.126 Time Step: 5.00 sec

STARE Satellite Design

- Cube-satellite: 10 x 10 x 34 cm
  - Boeing Colony II
- Dedicated F/2, 85mm diameter telescope
- 6 deployable solar panels provide power to satellite bus and LLNL payload
- ARM based payload processor
  - Triton PXA 270, 520 MHz, 64 Mb RAM
- CMOS imaging sensor
  - Aptina MT9M001, 1280x1024 5.2x5.2 micron pixel
- Next launch opportunity:
  - end 2014 / early 2015

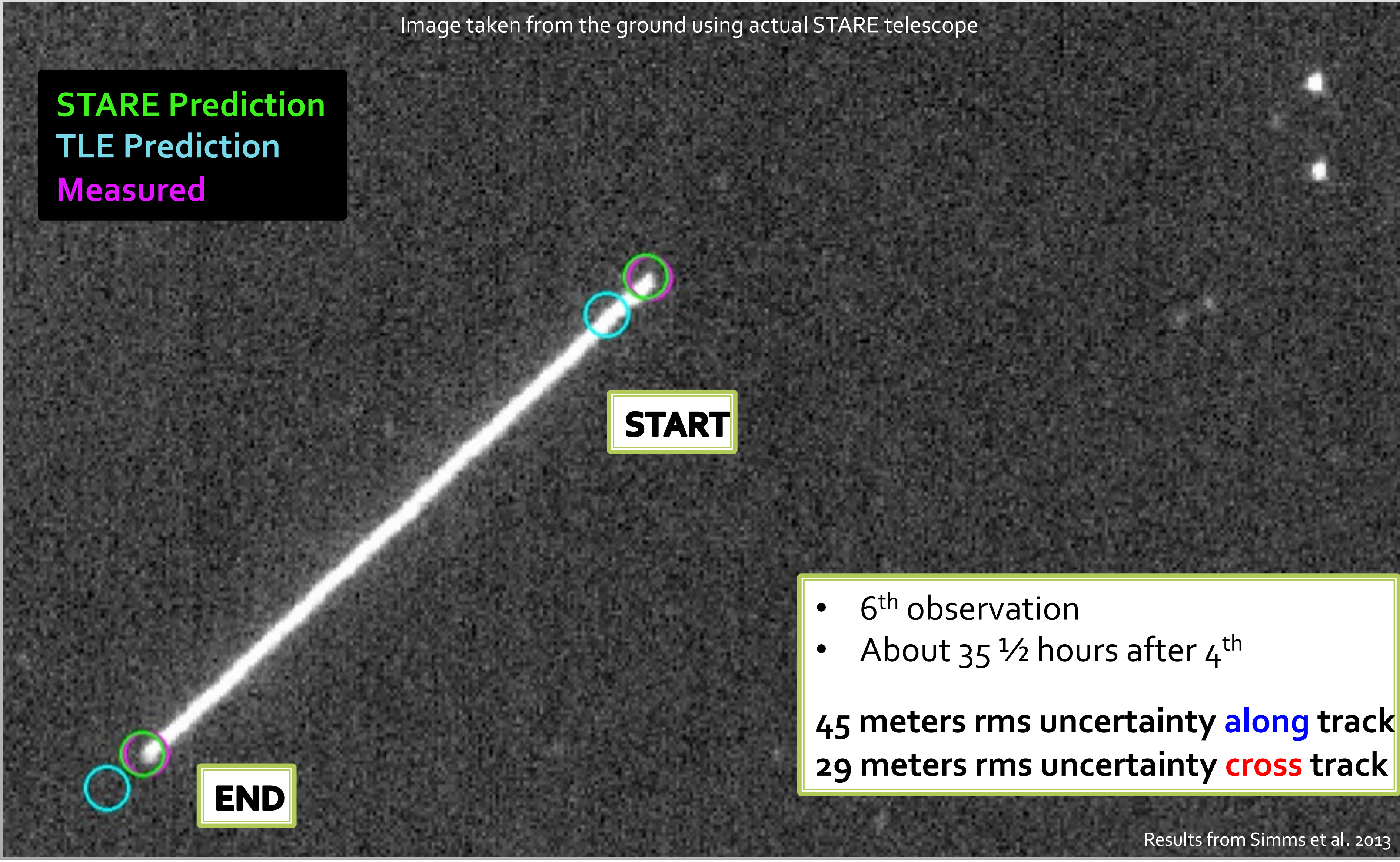






Images and payload data taken from Simms et al. 2013

Comparison of predicted and measured values for 6th observation



- 6th observation
- About 35 ½ hours after 4th

45 meters rms uncertainty along track
29 meters rms uncertainty cross track

On-board Processing Requirements

- Use automated routines to detect (faint!) streaks
  - The more on-board processing, the smaller the data volume
  - Characterization: angle, length, brightness, end-points
- Very low false alarm rate
  - Even a low false alarm rate can quickly overwhelm actual signal
- Very sensitive to faint streaks
  - Small targets, or targets that streak fast produce very dim streaks
- Very efficient algorithm
  - Target computer platforms are small and not very powerful (i.e., BeagleBoard, ARM-7/8/9 etc)

Algorithms under Consideration

- Hough transform
  - Computationally intensive
  - Affected by stars
  - Not very sensitive to faint streaks

- Path integrals through random sampling
  - Fast, easily parallellizable
  - Not affected by stars
  - Very sensitive

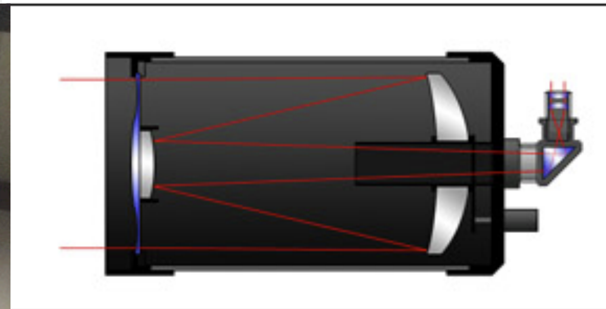
Telescope Setup to Acquire Faint Streaks

355 mm diameter aperture,
675 mm focal length

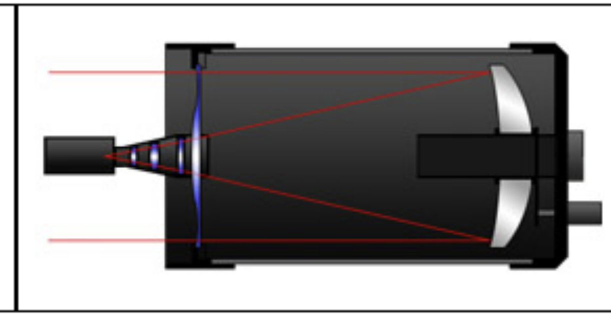
100mm diameter narrow field imager / tracker

50mm diameter wide field imager / finder

Cassegrain Focus F/11

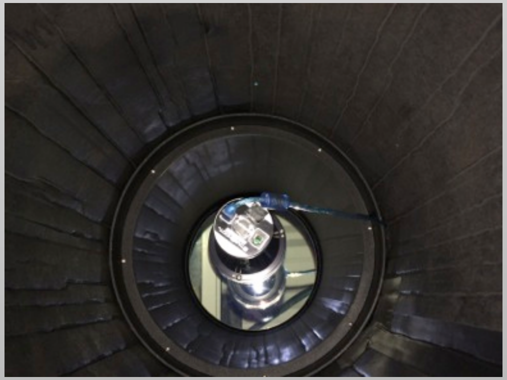


Prime Focus F/2



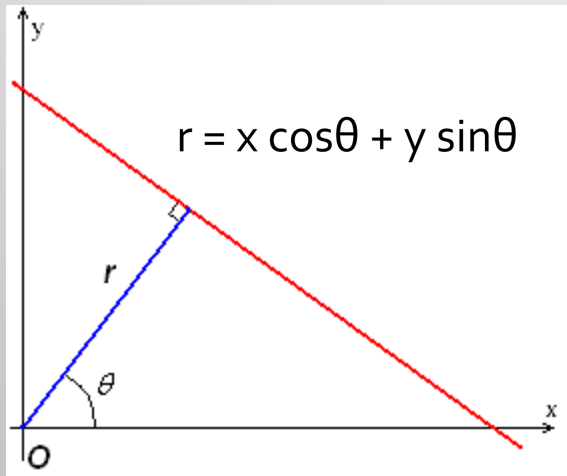
Prime focus F/1.8

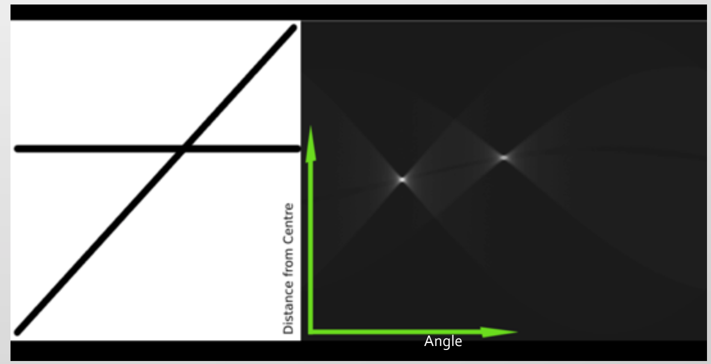
Prime focus camera



Automated Streak Detection using the Hough or Radon Transforms

- Hough transform





Points along a line in the (x,y) plane are transformed into sinusoids that intersect at a single point in the (r, θ) space

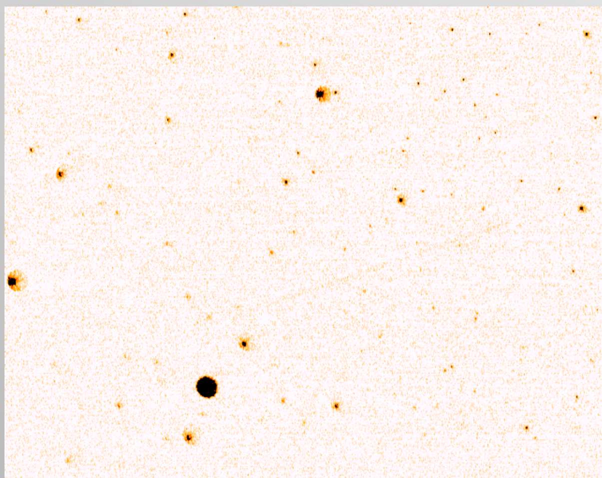
- The continuous Hough transform is equivalent to the more general Radon transform

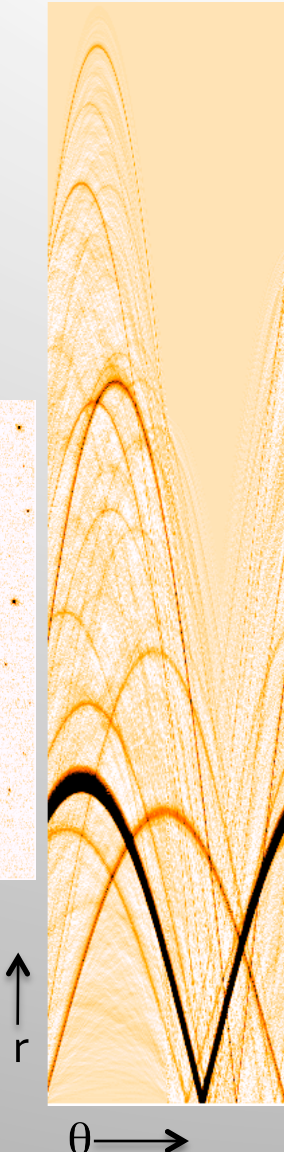
Let $f(\mathbf{x}) = f(x,y)$ be a continuous function vanishing outside some large disc in the Euclidean plane $\mathbf{R}^2$. The Radon transform, Rf, is a function defined on the space of straight lines L in $\mathbf{R}^2$ by the line integral along each such line:

$$Rf(L) = \int_L f(\mathbf{x})\,|d\mathbf{x}|.$$

Hough Transform

Processed frame





Difference frame

Hough Transform Results

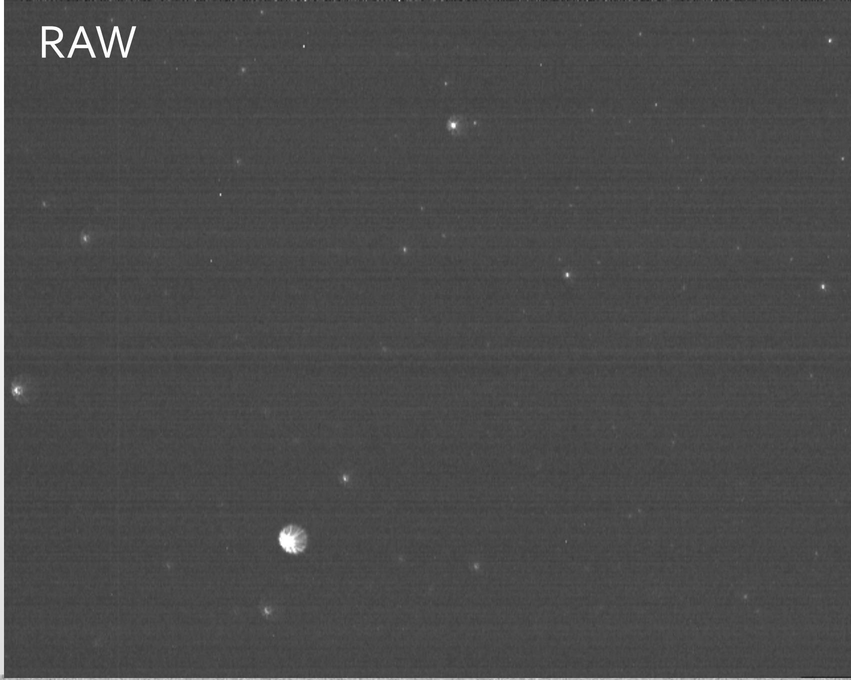
- Needs well calibrated and cleaned images – no stars
  - Difference images
  - Masking?
- High false alarm rate if going after faintest streaks
- Compute intensive: 0-360 degree, step 1 for a 640x480 image takes 0.83 seconds on 3.06 GHz Intel Xeon (17.0 seconds on BeageBone 1 GHz)
  - Almost certainly too coarse an angle step, may need 4x (0.25 degree) or 10x (0.1 degree)

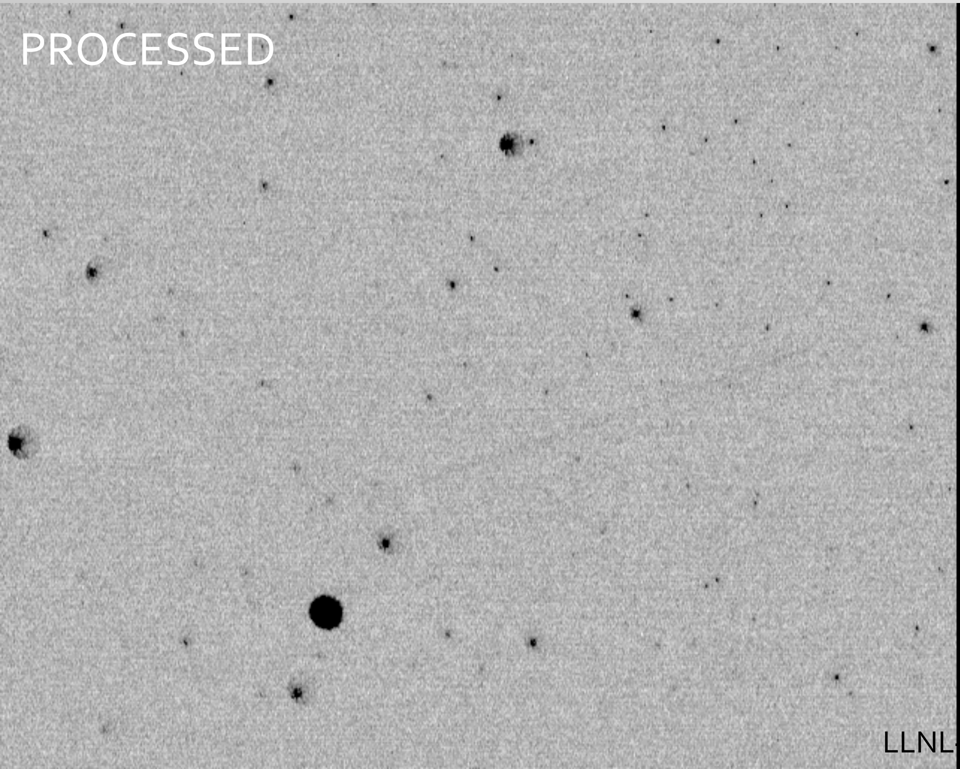
Random Path Integral

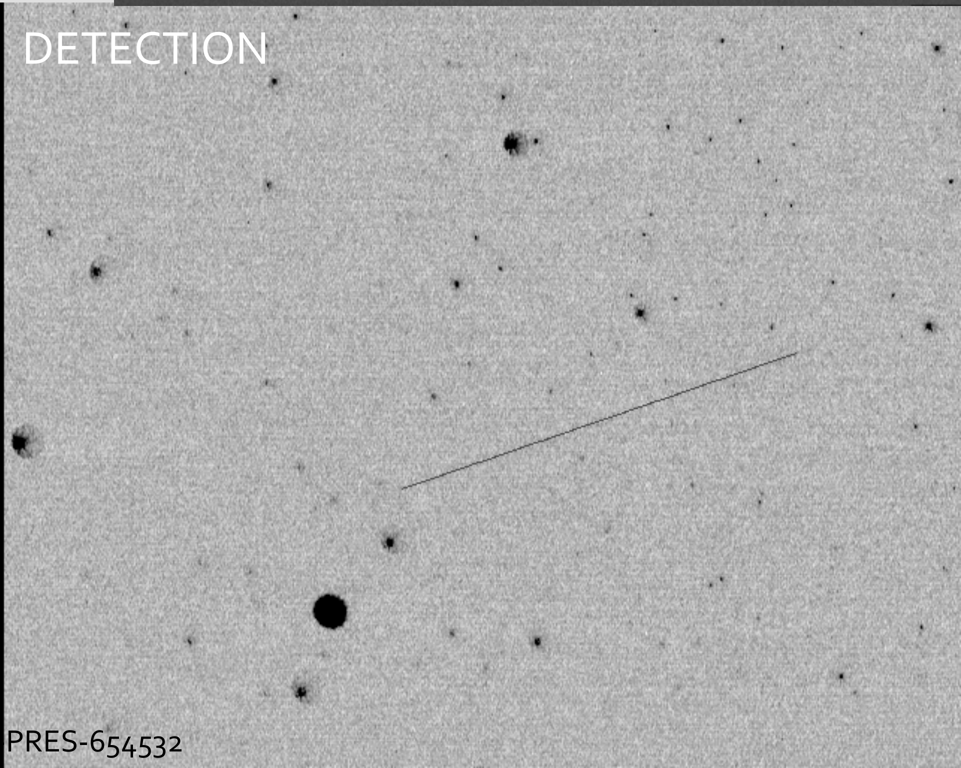
- Randomly drop line-segments onto image frame
  - Typically vary center coordinate (x,y) and angle. Keep length fixed to an appropriate value (typically 90% of expected streak length, but can be shorter)
- Count pixels along line-segment above a certain threshold (typically 1 sigma)
  - Do not factor in brightness – it is just a threshold
  - Stars are small circular objects (point-like) and do not look like streaks to this algorithm
- Flag a line-segment as a streak if the threshold count exceeds a certain limit (typically 180 out of a streak length of 280)

Effectiveness on Images with Stars

Target is a 10x10x15 cm cubesat at 500 km, moving at 7.6 km/s

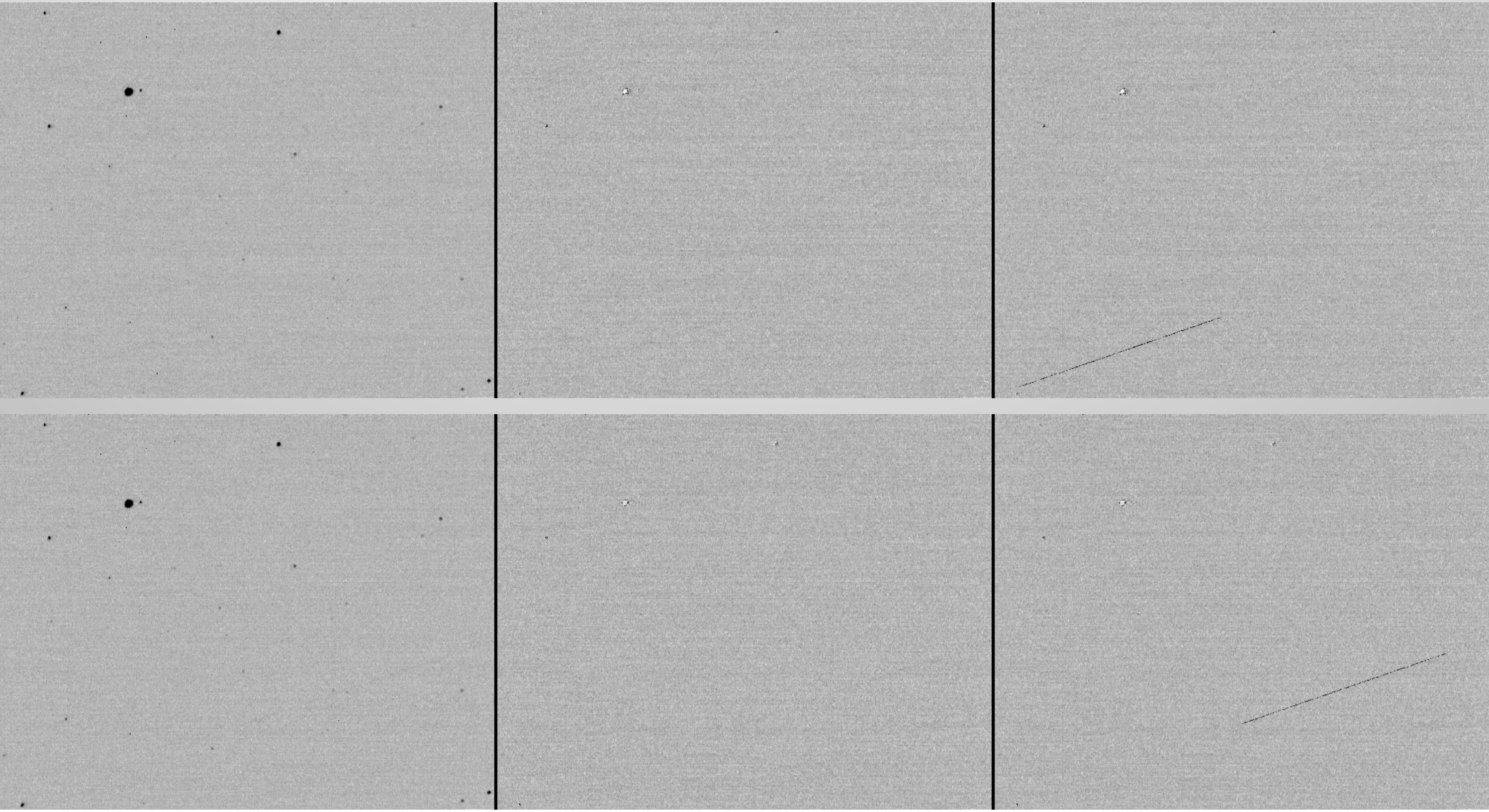






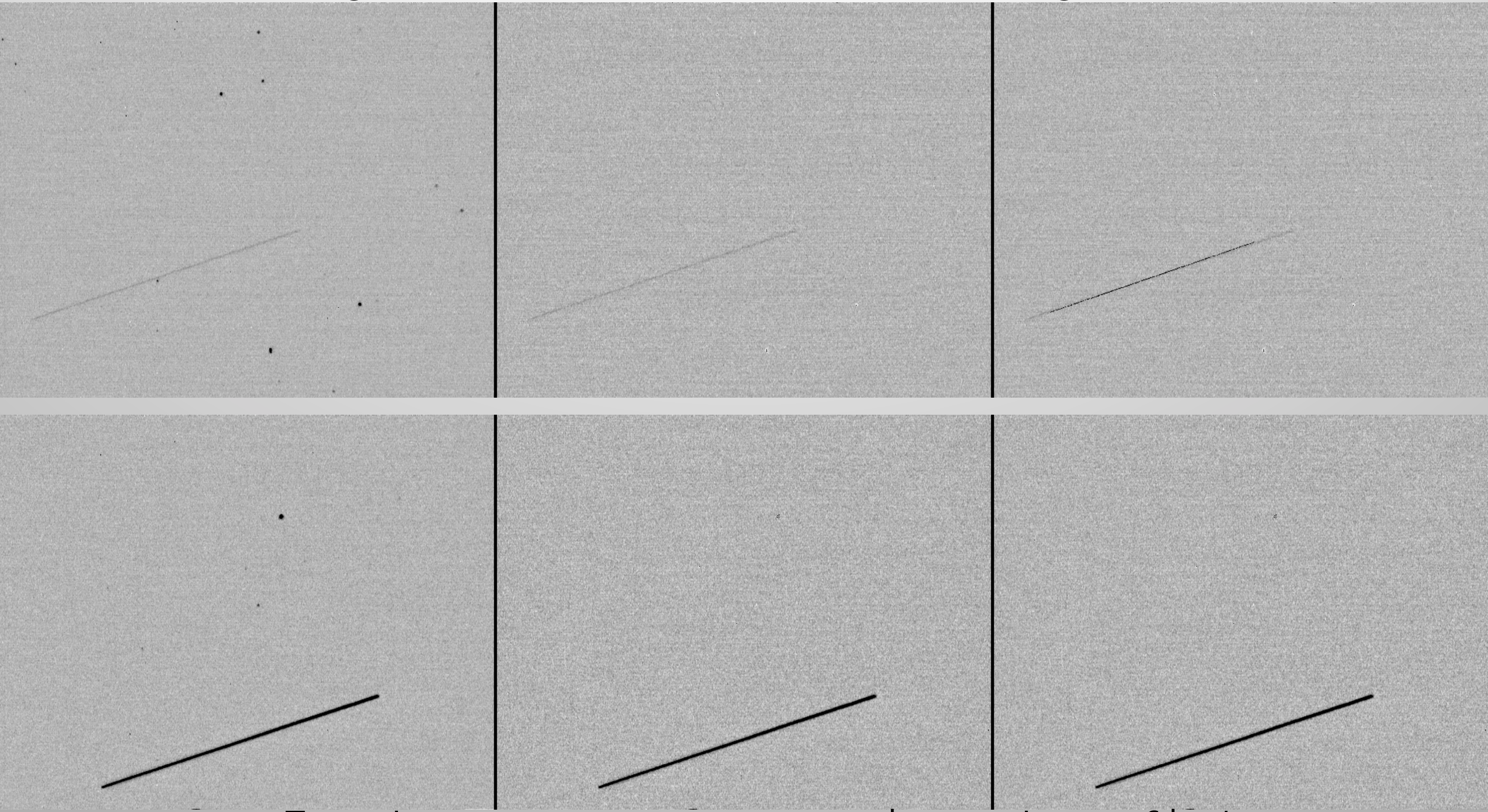
Effectiveness on Difference Images

Target is a 10x10x10 cm cubesat at 500 km, moving at 7.6 km/s



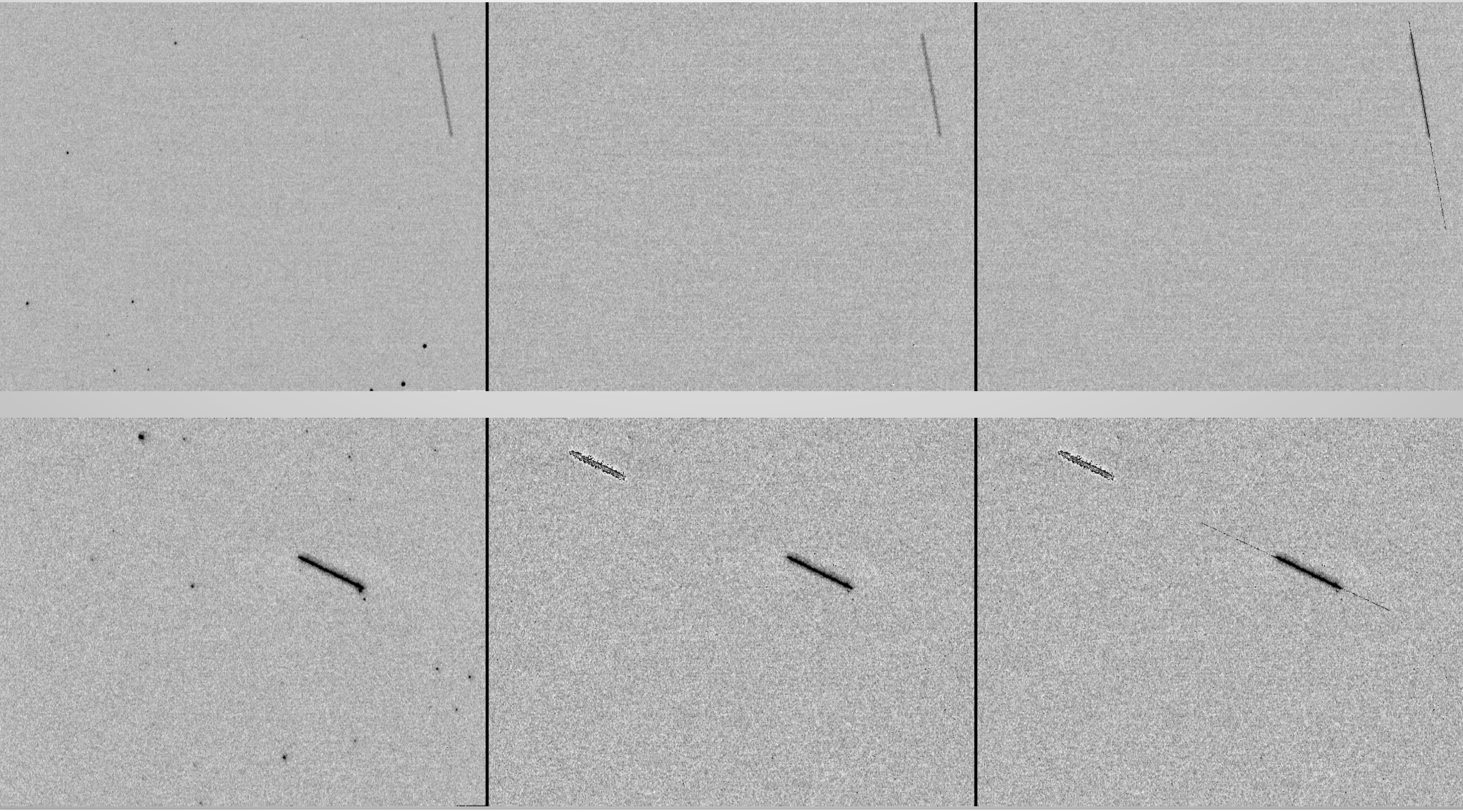
Effectiveness on Difference Images

Target is a 10x10x30 cm cubesat at 500 km, moving at 7.6 km/s

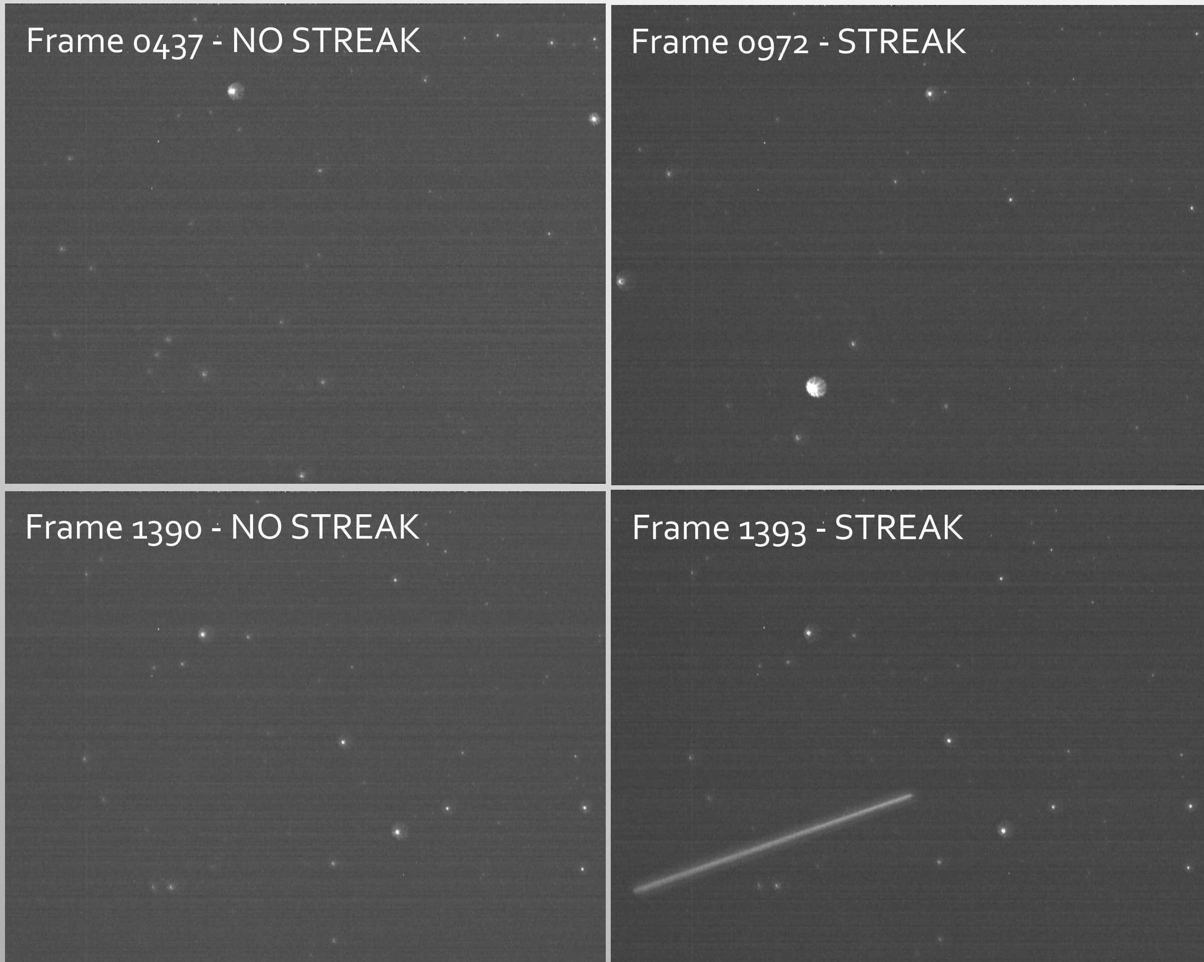


Target is a ~1x1x1 m upper stage at 500 km, moving at 7.6 km/s

Effectiveness on Difference Images - Interlopers



Accuracy



Setup:

- 3E6 lines per determination
- Random orientation (1-179°)
- 2 ADU threshold (0.7 sigma)
- 170/280 for streak
- Run 100x

Frame	Streak	Result
0437	No	100 N 0 Y
1390	No	100N 0 Y
0972	Yes	0 N 100 Y
1393	Yes	0 N 100 Y

Execution Speed

- 200,000 lines minimum if orientation known
- 3,000,000 lines minimum if not

- Single core 3.06 GHz Intel Xeon
  - 433,000 lines processed per second
  - 0.46 second to reach minimum requirement
- BeagleBone Black (1 GHz ARM-7 core)
  - 14,524 lines processed per second
  - 13.77 second to reach minimum requirement

Summary

- Random path integral method works well
  - Images with / without stars
- Easily parallellizable
- Will run well on next generation embedded systems (e.g., Nvidia Jetson TK1 – 326 GFLOPS)

- Tegra K1 SOC
  - Kepler GPU with 192 CUDA cores
  - 4-Plus-1 quad-core ARM Cortex A15 CPU
- 2 GB x16 memory with 64 bit width
- 16 GB 4.51 eMMC memory
- 1 Half mini-PCIE slot
- 1 Full size SD/MMC connector
- 1 Full-size HDMI port